Energy for Sustainable Development 71 (2022) 212–221

Contents lists available at ScienceDirect

Energy for Sustainable Development

Contribution of green roofs to energy savings in building renovations

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ARTICLE INFO

Article history:
Received 28 July 2022
Revised 23 September 2022
Accepted 24 September 2022
Available online xxxx

Keywords:
Green roof
Building renovation
Energy savings
Thermal management
Solar radiation

ABSTRACT

Reversing the consequences of climate change and achieving more resilient societies involves reducing CO_2 emissions and energy consumption, especially in sectors as important as construction. Green roofs, due to their particularities, imply a series of benefits, among which energy saving stands out. This implies a reduction in the consumption of resources and in CO_2 emissions, more evident in the case of the refurbishment of buildings. A comparison is proposed between the energy savings obtained by renovating only the roof and renovating the entire thermal envelope. This is done with three roof construction systems (including two green roofs) and in 6 Spanish cities that represent different climatic zones. The novelties provided by this research are based on the comparison of both renovation cases to obtain the influence of the roof with respect to the thermal improvement of the envelope. The energy savings obtained by renovating the roof are very similar in all cities, but after renovating the entire envelope, the savings increase as the climate gets colder. Determining the most influential variables in these savings, as well as the influence of the roof, allows choosing the most appropriate construction techniques to optimize the energy renovation of existing buildings.

Introduction

Within the field of architecture, new constructive and design solutions have been developed: (i) the design of buildings that are sustainable and climatically functional through passive bioclimatic systems (Freney et al., 2013; Krzemińska et al., 2017), (ii) the use of more sustainable or innovative materials (EPDM Roofing Association (ERA), 2010; Fabbri et al., 2021; Pérez et al., 2012; Shao et al., 2018), (iii) or the use of new systems that reduce the deterioration of the environment. Green facades (Lesjak et al., 2020; Serra et al., 2017), water-reserved roofs (Yang et al., 2015) or green roofs (He et al., 2020; Nektarios et al., 2021), are some of these solutions.

This increased concern for the environment comes along with an urgent global problem: climate change. In recent decades, a deterioration has become evident not only in the environmental surroundings, but also in the economic and social contexts (Huang et al., 2015). Air quality decreases (MDSA, 2022); its temperature increases especially in central areas of cities, an effect known as Urban Heat Island (UHI) (Akbari et al., 2001); climate events are becoming more extreme (heatwaves, intense rainfall that causes floods, etc.); and there is an increasing difference between dry and wet areas and seasons (International Institute for Applied Systems Analysis (IIASA), 2016).

One of the main causes of climate change is the increase in the presence of Greenhouse Gases (GHG) in the atmosphere, due to different factors, as changes in land use or the burning of fossil fuels (Ching & Shapiro, 2015). The same fuels that have been used for decades to generate electricity, which, in turn, is needed to activate air conditioning systems. In the specific case of Spain, the main source of electricity generation in 2021 was wind power (23.3 %) followed by nuclear power (20.8 %). An increase in the use of renewable sources helps to reduce the generation of GHG and, therefore, to minimize climate change and its consequences. In fact, from 2011 to 2021, CO_2 emissions in the production of electricity in Spain have been reduced by 55.2 % (Statista, 2021). But it is necessary to consider, not only the use of clean or renewable energy sources, but also to reduce energy consumption. Regarding the latest available data, in 2019 the building sector in Spain accounted for approximately 30 % of total energy consumption, with 17.1 % being the responsibility of the residential sector (Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2019; Ministerio de Transportes, 2020). To deal with these problems, in the European Union (EU) has established goals, such as the 17 Sustainable Development Goals (SDGs) (UN, 2022), and is has been proposed the improvement, by 2030, of energy efficiency by 32.5 % and a 40 % reduction in GHG emissions (EC, 2022).

Therefore, architecture, especially its most sustainable aspect, is presented as a useful tool when it comes to achieving these goals. In Spain, 60 % of the current housing stock was built prior to 1980 and is still in

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https://doi.org/10.1016/j.esd.2022.09.020

use without any integrated renovation (Ministerio de Transportes, 2020). Therefore, these are buildings that were built without complying with any standard that included aspects of thermal insulation in the envelope, since the first standard that refers to these aspects in Spain is from 1979. This implies that at present they are using buildings with high energy consumption that could be considerably reduced with improving the construction systems (insulation and air infiltrations) (Instituto Valenciano de la Edificación (IVE), 2011; Lerma et al., 2018; Presidencia del Gobierno (PG), 1979).

Among the possible sustainable architectural solutions, green roofs, due to particularities of their geometry and location (high incidence of direct solar radiation and high surface temperatures) and their vegetation cover, have been shown to reduce energy consumption, and CO_2 emissions. But its installation also means improving environmental aspects: reducing UHI (Liu et al., 2012; Tiwari et al., 2021), decreasing stormwater runoff and flood risk (Carte & Rasmussen, 2006; Dietz, 2007; Walters & Midden, 2018), or improving air quality (Mohammadi & Sobouti, 2016; Pandit & Laband, 2010). As they are solutions that not only try to minimize the impact of climate change, but also revert part of the problems generated with the recovery of green and natural spaces in the city, they are increasingly studied and applied in construction.

Also considering that a large part of the current housing stock in Spain lacks adequate insulation in the building's thermal envelope, green roofs still take on greater weight. Various investigations have shown that the energy savings obtained by installing a green roof in a building with little or no previous insulation are much more relevant than in the case of installing the same green roof in a well-insulated building, (Jaffal et al., 2012; Santamouris et al., 2007; Wong et al., 2003).

Research is proposed regarding energy savings and the reduction of CO_2 emissions obtained in different cases of thermal and energy renovation of a building. It is considered not only the integrated renovation of the house, with the thermal improvement of the entire building envelope, but also a possible refurbishment only by improving the roof construction system, analysing its influence on the total savings obtained in 6 different cities of the Spanish territory.

Materials and methods

The reference model proposed to renovate is a single-family semi-detached house (Fig. 1), whose main orientation is south and west. These facades are also the ones with the highest percentage of openings (21.1 % and 20.1 %, respectively), while the east facade is the party wall with the semi-detached house and the access is through the north facade, with 5.9 % of openings. The house, or reference model, is supposed to be built before 1980, so it does not have insulating material in the envelope.

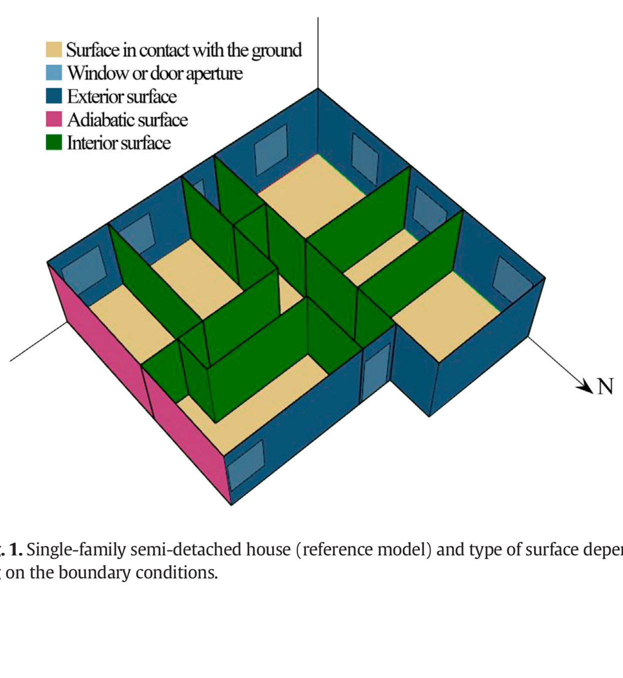

Fig. 1. Single-family semi-detached house (reference model) and type of surface depending on the boundary conditions.

Two refurbishment scenarios are proposed, with the intention of valuing the influence of the roof on the total energy savings obtained by improving the thermal envelope of the entire building (slab on grade, facades, roof, party wall and openings, both doors and windows). In both cases, the renovation is assumed under three possible roof construction systems: (i) traditional inverted with a gravel finish (model A), (ii) extensive inverted landscaped roof, with plastic nodular drainage layer, filter sheet, 10 cm thick substrate and vegetation with succulent species, in this case sedum (LAI = 0.80, Leaf reflectivity = 0.22, Minimum stomatal resistance (s/m) = 300) (model B), (iii) inverted intensive landscaped roof, with plastic nodular drainage layer, filter sheet, 60 cm thick substrate and vegetation with evergreen and turfgrass herbaceous species, in this case gramineous (LAI = 5.00, Leaf reflectivity = 0.30, Minimum stomatal resistance (s/m) = 120) (model C) (Table 1). In this case, only the layers above the support structure and slope formation are installed, since it is considered that, when carrying out the refurbishment, these two layers are in good condition.

Both green roof systems are designed self-sustaining. One of the problems derived from climate change is the accentuation of the differences between dry and wet areas and seasons. Spain is one of the European countries in which the problem of water stress is more important. If the forecasts are maintained, by the 2050s the usable water surface in the territory will be less than 95 % of the existing usable water surface in the 2010s. In fact, both in the data from the 2010s and in the predictions for 2050s, in the month of greatest water scarcity (July) more than 80 % of the population is in a situation of extreme water scarcity (International Institute for Applied Systems Analysis (IIASA), 2016). Under these circumstances, the irrigation of vegetated areas, both public and private, is one of the first water supplies to be cut, since it has no direct influence on human consumption (Reyes-Paecke et al., 2019). Cities such as Portland (Oregon, US), where water scarcity is also a major problem, design green roof with limited irrigation is encouraged (Schroll et al., 2011). It is therefore necessary to find a balance between the renaturation of cities and their benefits, and the use of water. For this reason, the study of the energy

Table 1
Main characteristics of the layers of the three roof construction systems; models A, B and C.

	Thickness (m)	Thermal conductivity (W/mK)
Model A		
EPDM Waterproof sheet	0.0012	0.25
XPS Thermal insulator	4.5–15.5[1]	0.033
Gravel	0.06	2.00
Model B		
EPDM Waterproof sheet	0.0012	0.25
Anti-root sheet	0.001	0.33
XPS Thermal insulator	3.5–14.0[1]	0.033
Plastic nodular drainage layer	0.04	0.33
Filter sheet	0.001	0.038
Substrate	0.10	0.435
Vegetation: sedum	0.10	–
Model C		
EPDM Waterproof sheet	0.0012	0.25
Anti-root sheet	0.001	0.33
XPS Thermal insulator	3.0–10.5[1]	0.033
Plastic nodular drainage layer	0.04	0.33
Filter sheet	0.001	0.038
Substrate	0.60	0.435
Vegetation: sedum	0.40	–

[1] The thickness is variable depending on the climatic zone, to adapt to the limited thermal transmittance of the roof in each of the cities (Table 3). In any case, a minimum layer of thermal insulation of 3 cm is provided to avoid thermal bridges due to the amount of water stored in the substrate.

performance of self-sustaining green roofs is proposed, which do not require any water supply through irrigation systems.

When making a comparison between construction systems, other variables must also be considered, in addition to the energy savings achieved, which imply a series of advantages that prompt the choice of one model over another. Table 2 indicates important aspects from a sustainable perspective, such as environmental and social benefits, as well as variables that are especially decisive in the case of installing the roof on an existing building, such as its self-weight or the construction cost. For the calculation of these last two variables, the layers described in Table 1 have been considered.

Of the two refurbishment scenarios, first, a renovation only of the roof is proposed. Secondly, the simulation of the integrated renovation of the entire building envelope is carried out. The thermal inertia of construction systems is improved by introducing insulating materials, having to reach the thermal transmittance values indicated in the current standards: the *Código Técnico de la Edificación* (CTE) and the *Documento Básico de Ahorro de Energía* (DB-HE) (Ministerio de Fomento (MF), 2019). The standards themselves divide the Spanish territory into 6 climatic zones (α-A-B-C-D-E) and for each of them they establish thermal transmittance limit values (Table 3). The climatic zone α is characteristic of the Canary Islands. The rest of the zones range from A, warmer and with higher limit thermal transmittance values, to E, colder and with more restrictive values. In the reference model, as it was designed without thermal insulation in the envelope and with a construction system with greater air infiltrations, the thermal transmittances obtained are much higher than the maximum required by standards. Only in the access door to the house, the existing design shows a lower transmittance than required (4.2 W/m^{2}K), so this will be the only element of the envelope that will not be improved in the refurbishment, maintaining in all climatic zones this value. In addition, due to the improvement of the construction systems, air infiltrations will be considerably reduced compared to the reference model.

According to this distribution by climatic zones, the analysis has been carried out in 6 Spanish cities, which represent each of the 6 climatic zones (Fig. 2). The variables that determine this climatic classification are the outdoor temperature and direct solar radiation, so Figs. 3 and 4 show the average values for each city.

Therefore, a total of 42 simulations are carried out. In each of the 6 cities, the reference model (without insulation) and models A, B and C are analysed, in the two refurbishment scenarios: only the roof and integrated renovation of the entire thermal envelope. For its execution, the EnergyPlus (U.S. Department of Energy's Building Technologies Office (DOE BTO), n.d.) calculation engine has been chosen. It is an open source simulation engine, which allows it to be constantly improved and updated (Bravo, 2016). Moreover, in Spain the standards allow the use of an official program (for example, the *Herramienta Unificada LIDER-CALENER* (HULC)) to carry out energy simulations, but also reference calculation engines, such as EnergyPlus (Ministerio de Industria, 2015).

Table 3
Thermal transmittances of the envelope elements in the reference model and in the different climatic zones in accordance with current standards in Spain.

	Reference model	Climatic zones					
		α	A	B	C	D	E
Roof	1.40	0.50	0.44	0.33	0.23	0.22	0.19
Facade	3.02	0.56	0.50	0.38	0.29	0.27	0.23
Slab on grade	5.25	0.80	0.80	0.69	0.48	0.48	0.48
Party wall	2.52	0.90	0.80	0.75	0.70	0.65	0.59
Window	5.69	2.70	2.70	2.00	2.00	1.60	1.50
Door	4.20	5.70	5.70	5.70	5.70	5.70	5.70

To improve data entry and the geometric design of the building, it has been worked with the graphical interface OpenStudio (Alliance for Sustainable Energy (ASE), n.d.) that allows graphic tasks to be carried out through SketchUp. In the case of green roofs, the heat transfer model in the vegetation and substrate layers is very complex, but EnergyPlus integrates a system developed by Sailor (2008) which, based on the Frankenstein and Koenig FASST model (Frankenstein & Koenig, 2004) establishes a sufficiently accurate simplification of the heat transmission phenomena that occur in these layers (Ouldboukhitine et al., 2014). Various subsequent investigations have validated this model and its implementation as part of EnergyPlus (Ascione et al., 2013; Yazdani & Baneshi, 2021; Ziogou et al., 2017).

The different simulations will make it possible to compare the energy savings obtained by renovating the roof and by renovating the entire envelope. When comparing each of the A-B-C models (according to the chosen roof system) with the reference model and in each of the 6 cities, it will be possible to observe what influence the roof has, due to its characteristics of high direct solar incidence and high surface temperatures, in the total savings obtained by improving the entire thermal envelope. Likewise, by means of the CO_2 emissions equivalence ratios available for Spain, these energy savings of final energy (considering electricity as the only source of energy for the building) can be translated into equivalent kilograms of CO_2 that will not be emitted into the atmosphere (Fernández-Salvador, 2012).

Results and discussion

Energy savings

According to the results obtained in the simulations, it can be observed that by renovating only the roof, regardless of the construction system (A-B-C), energy savings are always achieved with respect to the reference model (Fig. 5). The amount of total annual final energy saved with this refurbishment increases as the climate gets colder and

Table 2
Comparison between models A, B and C as a guide for their election as renovation's construction systems.

	Model A	Model B	Model C
Environmental benefits	–	• UHI reduction • Air pollution reduction • Environmental noise reduction	• Improved biodiversity[1] • UHI reduction • Air pollution reduction • Environmental noise reduction • Runoff water reduction[1] • Runoff water quality improvement[1]
Social benefits	–	• Visual enjoyment of green spaces • Physical and mental health improvement	• Visual enjoyment of green spaces • Access and use of green spaces • Physical and mental health improvement
Self-weight (kg/m^2)	113.35 - 116.92[2]	163.51–166.87[2]	948.22–950.66[2]
Construction cost (€/m^2)	38.30–49.33[2]	85.69–95.47[2]	202.33–210.17[2]

[1] These benefits are also obtained with an extensive green roof (model B), but to a lesser extent.
[2] According the variable thickness of the thermal insulator layer.

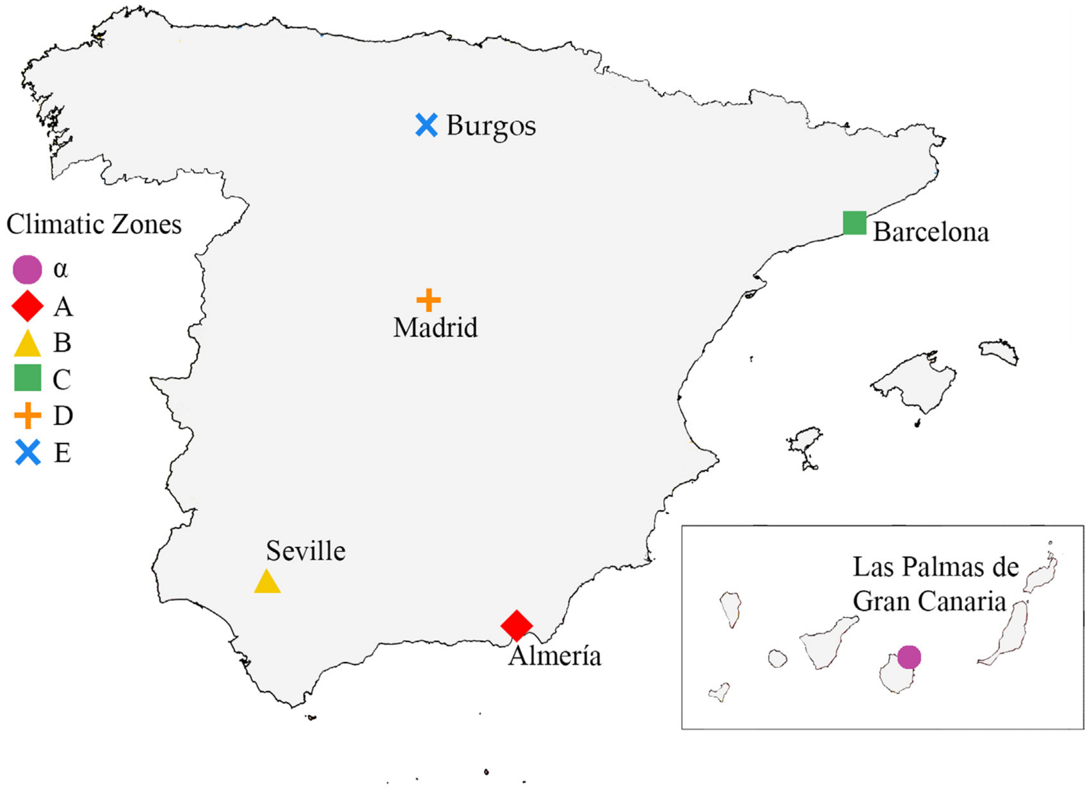

Fig. 2. Location of the cities and climatic zone of each one.

with greater daily and annual temperature variations. In the case of Burgos, the difference between the maximum and minimum annual average temperature is 9.1 °C, and in Madrid it is 10.7 °C. In Las Palmas de Gran Canaria, Almería and Barcelona the difference between these two temperatures is 4.3 °C, 6.4 °C and 4.3 °C, respectively. In the case of Seville, climatic zone B, the difference is 10.6 °C, similar to Madrid. But both the maximum and minimum annual average temperature are higher than those of Madrid, climatic zone D. Therefore, the combination of cold weather and large temperature variations (these are cities that are inland, far from the sea, that works as a thermal regulator) represents an increase in the energy savings obtained after the renovation of the roof.

This same behaviour is observed in the case of integrated renovation of the entire thermal envelope, regardless of the roof system (A-B-C). In the first place, it should be noted that in this refurbishment case, the total annual final energy consumption is greater than in the reference model only for the city of Las Palmas de Gran Canaria. This is because this city, climatic zone α, has an outdoor temperature with few daily and annual variations. In addition, as can be seen in Fig. 3, the maximum and minimum annual average temperatures are above 19 °C, staying

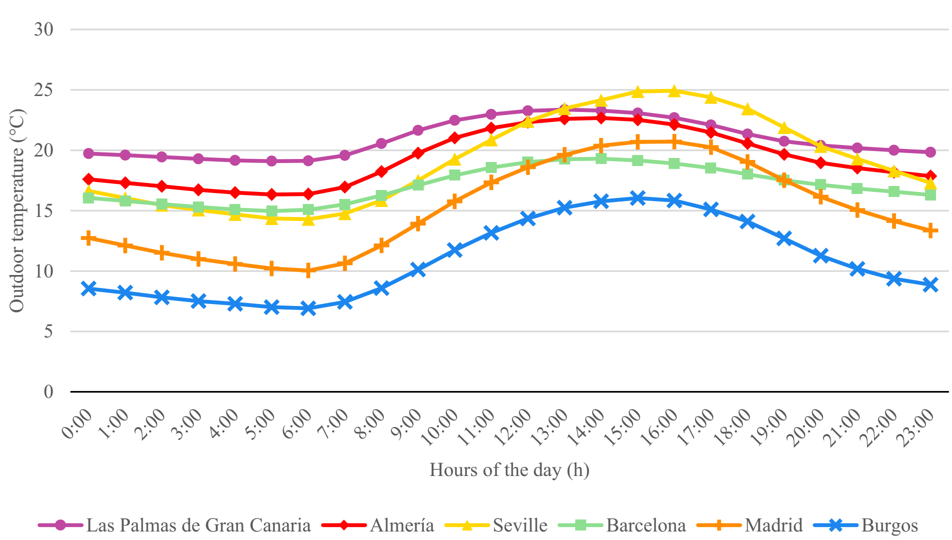

Fig. 3. Average annual outdoor temperature per hour of the different cities.

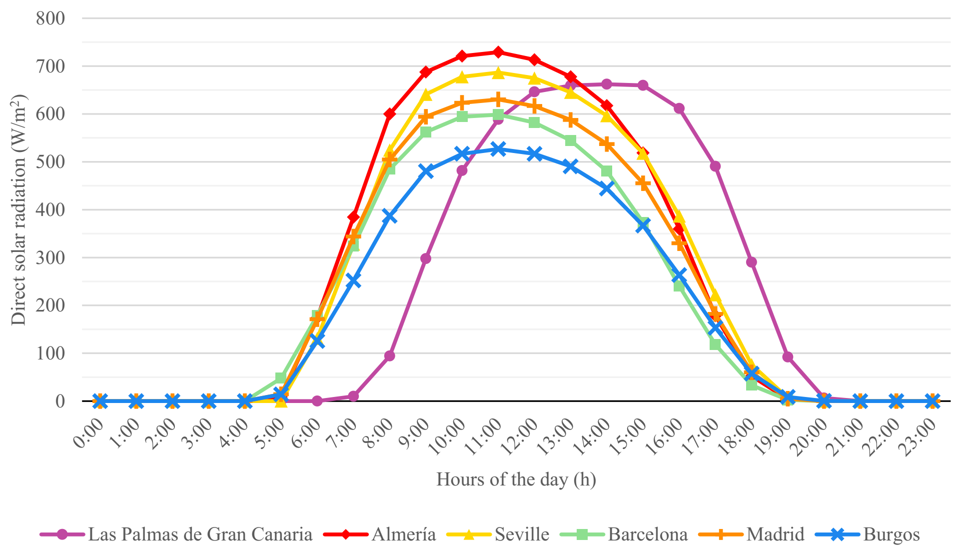

Fig. 4. Average annual direct solar radiation per hour of the different cities.

very close to the indoor comfort temperature established by Spanish standards (23–25 °C) (Ministerio de la Presidencia (MP), 2021).

It should also be considered that in today's cities there are other types of buildings, higher. The study of the extensive green roof model (B) in a warm climate is considered, but keeping in mind that, as can be seen in Table 4, the energy savings produced by renovating the roof are very similar in all the cities and with all the models (with approximate values between 9 % and 13 %). The modelled house, maintaining its orientation and distribution, is proposed as part of a multi-storey building, in which only the roof is renovated to determine the energy savings that the improvement of the roof represents with respect to the reference model based on the height of the building. In this case, there is an exponential decay in the annual energy savings obtained, both air conditioning and total savings, with the increase in the number of floors, especially between one floor (single-family house) and three. The decreasing curve traced by the annual savings with respect to the total final energy consumption begins to describe a flatten trajectory from the fourth floor, with the energy savings with respect to the reference model being around 2 %. For a number of floors greater than five, it will be assumed that the installation of an extensive green roof in renovation will not achieve total annual energy savings greater than 2 %.

Regarding the geometry and location of the single-family house, the main orientations are south and west, with these facades receiving the highest incidence of solar radiation in the northern hemisphere. In addition, these facades are the ones with the highest percentage of openings. After the renovation, the thermal inertia of the envelope is increased by improving its transmittance and adding a layer of insulating material, but the heat gains obtained by these facades are still very high. This is due to its orientation and the fact that the refurbishment has only improved the insulation of the envelope, but no solar control elements have been provided to limit the incidence of direct solar radiation on these more exposed facades. Therefore, the heat reaches the interior of the building, although attenuated and delayed in time thanks to the insulating material, and heats the spaces. Since a minimum ventilation established by standard has been designed and air infiltrations from the outside have been reduced by improving the construction systems, this heat that reaches the interior, however little it may be, cannot be dissipated. That is why a correct sustainable design must consider solar control elements that reduce the direct incidence of the sun on the envelope or pair the improvement of inertia with an increase in the ventilation of the spaces. In cold seasons, with predominance of the use of heating systems, the increase in ventilation involves the entry of cold air from outside, as well as the loss of heat produced inside the different spaces. In addition, in this period the heat gains inside the rooms, due to the orientation, are positive, reducing the heating energy consumption compared to the reference model. In cold seasons,

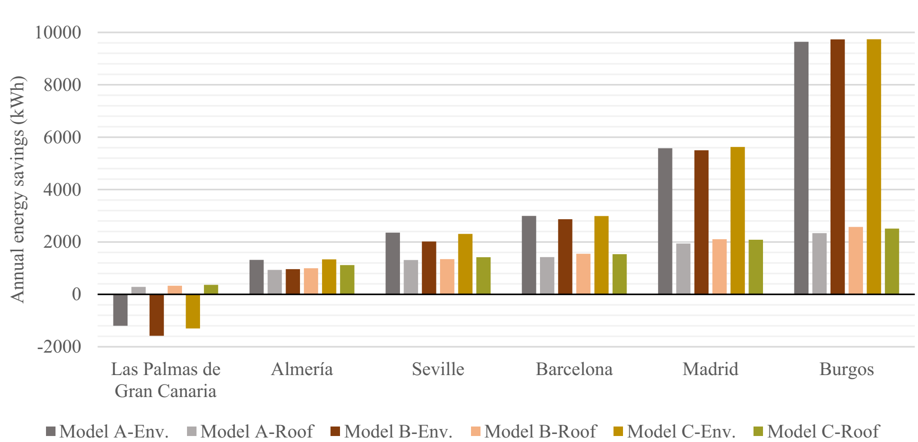

Fig. 5. Energy savings regarding the total annual site energy consumption of the reference model of each model (A-B-C) in the two renovation scenarios: only roof (Roof) and envelope (Env.).

Table 4
Savings in total annual site energy consumption (%) comparing the reference model with the A-B-C models in the two renovation scenarios: only roof (Roof) and envelope (Env.). In each case, the influence (%) of the A-B-C roofs is determined with respect to the entire envelope.

	A-Env.	A-Roof	A-Influence	B-Env.	B-Roof	B-Influence	C-Env.	C-Roof	C-Influence
Las Palmas de Gran Canaria	−17.27	4.12	−19.26	−22.75	4.72	−17.18	−18.71	5.2	−21.75
Almería	12.42	8.85	71.26	9.11	9.4	103.18	12.63	10.59	83.85
Seville	19.47	10.83	55.62	16.67	11.12	66.71	19.06	11.72	61.49
Barcelona	23.97	11.39	47.52	22.97	12.41	54.03	23.93	12.27	51.27
Madrid	34.82	12.12	34.81	34.36	13.15	38.27	35.14	13.02	37.05
Burgos	46.00	11.16	24.26	46.45	12.27	26.42	46.47	11.98	25.78

therefore, the minimum ventilation required by the standards is sufficient to achieve energy savings and adequate health and thermal comfort conditions inside the house. On the other hand, in warm seasons, an increase in ventilation is desirable, since in this period the warming of the interior of the rooms is not desirable as it implies an increase in the consumption of refrigeration to cool the interior spaces. Specifically, greater ventilation is advisable at night, when there is no incidence of direct solar radiation on the envelope, the heat accumulated by these elements throughout the day is transmitted to the interior (delayed in time thanks to the increase in inertia) and outdoor temperatures decrease, being closer to, or even below, the indoor comfort temperature (depending on the city and climate zone).

As can be seen in Fig. 4, direct solar radiation in Las Palmas de Gran Canaria is high, with the maximum average annual being above 650 W/m^2. In this case, heat gains inside the spaces due to orientation, increased inertia and minimal ventilation considerably increase cooling energy consumption. Especially in this city where for much of the day and year the outdoor temperature is within the range of indoor comfort temperature, or close to it. Therefore, increasing insulation from the envelope without increasing ventilation is energetically detrimental in this location. In the case of renovating only the roof, the air infiltrations and the lack of insulation of the facades allow the heat that enters the interior of the spaces to dissipate more easily without cooling systems. It should be noted that, in the case of renovating the entire envelope in any of the cities, the design of solar control systems or the increase in ventilation in warm seasons would lead to even greater energy savings than those obtained.

But this problem becomes less evident in cities with less solar radiation and, especially, less importance of cooling energy consumption with respect to total energy consumption (because they are located in colder climates). This justifies that in cities such as Burgos or Madrid, in which the annual cooling consumption of the reference model represents 1.2 % and 9.9 % of the total, the total annual savings obtained have been greater. Meanwhile, in cities such as Almería (19.8 %), Seville (22 %) or Barcelona (12.9 %), the influence of cooling energy consumption in the reference model was already much greater, increasing due to the renovation of the entire envelope, justifying that the total savings obtained are more limited. In the cases of Burgos and Madrid, moreover, the greater influence of energy consumption for heating in the reference model will be compensated by a decrease after the refurbishment due to the heat gains derived from the orientation, the increase in inertia and the minimal ventilation.

Regarding the roof construction system, it is observed as in all cities, in the case of renovating only the roof, the extensive (B) and intensive (C) systems achieve greater annual energy savings than the traditional model with a gravel finish (A). In addition, it is observed that in warm climates (Las Palmas de Gran Canaria, Almería, Seville and Barcelona) model C presents savings that are very similar or higher than those of model B. This is partly due to the type of vegetation (gramineous). It is a tall vegetation that allows an air gap to be created to dissipate the heat accumulated under the vegetation and above the substrate, it has a high LAI so the shadow on the substrate will be dense, and also it is not able to regulate the opening of its stomata, producing greater heat losses by evapotranspiration, especially in summer. On the other hand, model B presents greater savings in colder climates (Burgos and Madrid), since the vegetation (sedum) is low, with a lower LAI, less shade on the substrate, a greater direct incidence of solar radiation in it and this vegetation has the ability to regulate the opening of its stomata and limit heat losses by evapotranspiration in times of water scarcity, such as summer. In the case of cities where cooling consumption predominates, model C achieves better energy performance than model B, which will work better in those cities where heating energy consumption predominates.

Influence of the roof

It can be seen in Fig. 5 how the difference between the energy savings obtained only with the roof and with the entire envelope also increases as it is analysed cities in colder climates and with greater daily and annual thermal variation. In Burgos, which also has the lowest maximum average annual solar radiation of the 6 cities, the difference between the savings of both renovation assumptions is much higher. At the opposite extreme, Almería, with a warm, dry climate and high solar radiation, the energy savings obtained with model B in both renovation scenarios are practically the same. This indicates that, in relation to annual energy savings, the influence of the roof with respect to the entire envelope varies depending on the type of climate, that is, the outdoor temperature and solar radiation (Fig. 6).

As can be seen in Fig. 6, the influence of the renovation of the roof on the energy savings obtained after the renovation of the entire envelope describes a profile similar to the average annual outdoor temperature of each of the cities. In the case of Las Palmas de Gran Canaria, the only city with an average annual temperature above 20 °C, the influence of the roof is negative. As mentioned above, in the assumption of improving the entire envelope in this city, the energy consumption produced is greater than the total energy consumption of the reference model. Specifically, there is an increase in consumption of 17.27 %, 18.71 % and 22.75 % in model A, B and C, respectively. In contrast, only the improvement of the roof represents energy savings of 4.12 %, 4.72 % and 5.2 %, respectively. Therefore, the increase in energy that occurs between the renovation with the roof and with the entire envelope is 21.39 % in model A, 27.47 % in model B and 23.91 % in model C. Therefore, the percentage of influence of the roof with respect to the total envelope is negative, as can be seen in Table 4.

In the rest of the cities, the influence of the roof is positive and remains, in most cases, below 100 %, since the energy savings obtained with the roof is less than the savings obtained by renovating the entire envelope. It can also be seen how this influence of the roof decreases from Almería to Burgos in accordance with a decrease in the average annual temperature. The lower the outdoor temperature is, the lower influence of the roof is recorded. In Almería, in model B, the influence becomes greater than 100 % because the energy consumption obtained after renovating the roof is less than the energy consumption after renovating the entire envelope.

Different factors that explain this behaviour must be taken into account. On the one hand, cities in climates with higher outdoor temperatures show high values of solar radiation. On the other hand, the roof, due to its location (in this case horizontal) receives greater direct solar radiation even than the south facade. Greater incidence of solar radiation means reaching higher surface temperatures on the outer surface

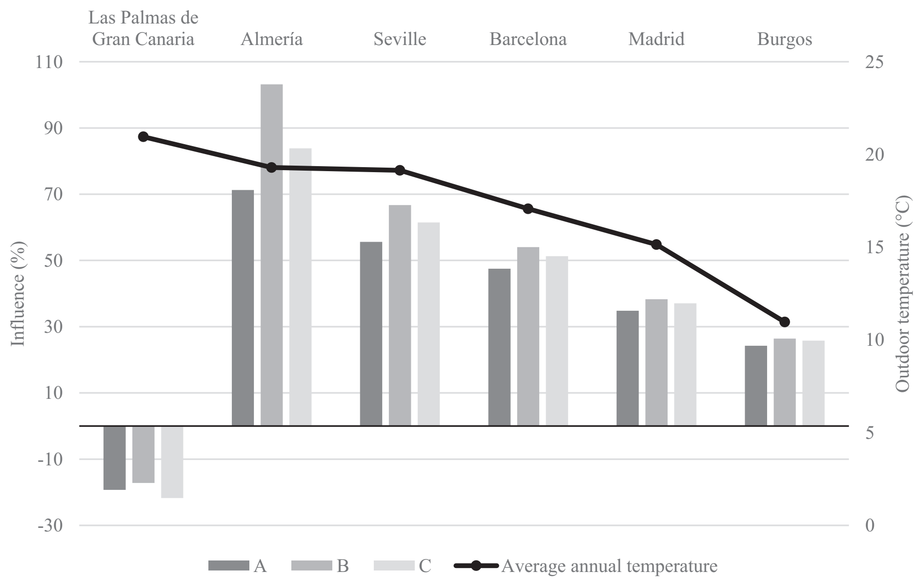

Fig. 6. Influence of the roof regarding the total envelope in relation to the energy savings obtained after renovation in both scenarios, for each roof construction system (A-B-C). Average annual outdoor temperature of the cities.

of the roof. Increasing the thermal inertia of the roof implies that these higher exterior surface temperatures are not fully transmitted to the interior. In these cases, the thermal improvement of the roof represents a very important energy savings, presenting an influence of the roof close to or greater than 50 % with respect to the savings obtained by improving the entire envelope. Cities such as Almería (climate zone A), Seville (climate zone B) and Barcelona (climate zone C) have high outdoor temperatures and intense solar radiation that cause high surface temperatures to be reached on the roof. Which, thanks to the improvement of the thermal inertia, will be transmitted to the interior, but attenuated and delayed.

However, in cities with colder climates, regardless of the incident solar radiation, the most determining factor is low temperatures and protection from them. As has already been mentioned, these are cities with the greatest influence of heating consumption with respect to total consumption. In these cases, it is necessary that the largest number of square meters of the envelope in contact with the outside air be properly insulated to prevent positive heat flows from cold entrance and negative heat flows that are produced by heat losses from inside heated, due to lack of inertia. The roof only accounts for 47 % of the surface of the envelope in contact with the outside air. Therefore, in cities such as Burgos (climatic zone E) and Madrid (climatic zone D), the renovation of the roof supposes an influence of less than 50 %.

The energy savings obtained by renovating the entire envelope with each of the construction systems (Fig. 5) can also be justified in these terms. In warm climates, very similar savings are obtained with the models with a gravel finish (A) and with an intensive green roof (C), while the model with an extensive green roof (B) performs slightly worse. The greater incidence of solar radiation on the substrate surface of the model B, due to the characteristics of the vegetation, increases the surface temperature, the transfer of heat to the interior and, therefore, the cooling energy consumption. In the case of cities in cold climates, the savings of the three models are very similar, even reaching, in Burgos, greater savings in model B than in A. The greater incidence of solar radiation on the substrate surface and the increase in surface temperature, in this case, represent a benefit by reducing heating energy consumption, which is much more relevant in these cities located in colder climates.

Regarding the relationship between the construction system and the influence of the roof, it can be seen that the percentage of energy savings compared to the reference model after renovating the roof is very similar in the three models in the 6 cities (with approximate values between 9 % and 13 %, with the exception of Las Palmas de Gran Canaria). Within this similarity, however, what has already been mentioned can be observed: in warm climates, savings are greater after renovation with model B and C than in the model A, and greater in model C than in model B. Meanwhile, in cold climates, the percentage of savings after roof renovation is greater in model B than in model C, and in both cases greater than in model A. Regarding the energy savings obtained in relation to the reference model, when renovating the entire envelope, the percentages already differ more between cities (values between 9 % and 46 %). Regarding the models, the savings are very similar between models A and C in warm climates, while model B presents lower savings values. In cold climates, the percentage of savings after renovating the envelope with model B increases, reaching, in the case of Burgos, to be greater than the percentage of savings of model A. These factors justify that in the case of model B, with lower energy savings when renovating the entire envelope, but similar percentages of energy savings to the rest of the models in the case of renovating only the roof, the influence of the roof with respect to the entire envelope is greater, especially in warm climates (Fig. 6).

Fig. 7 shows the specific case of this model B with the intention of graphically justifying the influence of the roof with respect to the integrated renovation of the envelope. It can be seen how the energy savings obtained by the thermal improvement of the roof are very similar in all the cities. But as climates get colder, the energy savings obtained from renovating the entire envelope is significantly higher. This difference between savings explains the lower influence of the roof in cold climates, despite the fact that the savings obtained after rehabilitating the roof are very similar in all cities (both in warm and cold climates).

Economic study and CO_2 emissions

If approximate calculations are made of the construction cost of both renovation options, it can be seen how the influence of the roof is even more important. The Basic Building Module (MBE, from the Spanish words *Módulo Básico de Edificación*), published by the *Instituto Valenciano de la Edificación* (IVE), is taken as the basis for the calculation of the cost of material execution by square meter (€/m^2) of a building (IVE, 2022). In this case, the MBE is consulted for the refurbishment of a residential building, an isolated single-family house, with an average usable area of 70 m^2 and with a medium level of finishes. The MBE,

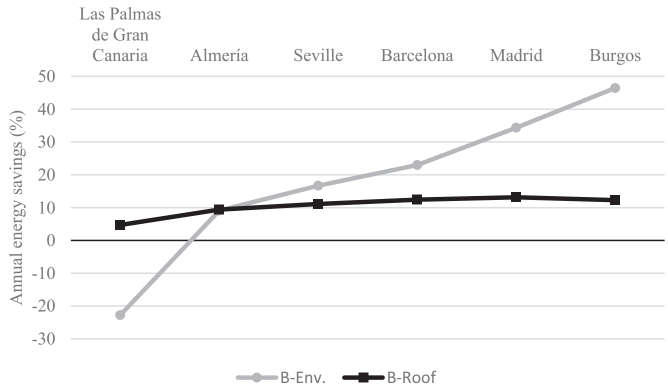

Fig. 7. Energy savings of model B regarding the reference model in the two renovation scenarios: only roof (Roof) and envelope (Env.).

considering a level of "integrated renovation" (the maximum possible) in the envelope (roof, facades and windows), is 154.81 €/m^2 for the date of consultation (July 2022). In the case of renovating only the roof, with the same level, the MBE is 25.80 €/m^2.

Considering that the modelled house has an area of 77.2 m^2, the cost of each renovation case would be, according to the MBE, of:

- 11,951.33 € for the renovation of the entire envelope (it should be noted that the consulted MBE does not consider the thermal improvement of the slab on grade, a fact that would increase the cost of this renovation).
- 1991.76 € for roof renovation.

Table 5 shows the economic equivalence of the energy savings achieved in the different cities for each renovation case. To do this, the final energy consumed is multiplied by the value of the electricity rate (€/kWh), provided by Eurostat for the first half of 2021 (latest data available when consulting: July 2022) (Eurostat, 2022). Considering a domestic energy consumption with annual values between 5000 and 15,000 kWh, the value of the rate for Spain, including taxes and fees, is 0.1869 €/kWh.

It can be seen how in the case of Almería (climate zone A), Seville (climate zone B) and Barcelona (climate zone C) the economic savings achieved by renovating the roof are greater than 50 % of the savings by renovating the entire envelope. However, the construction cost of the case of renovating only the roof is 16.7 % of the cost of renovating the entire envelope.

The construction cost values provided are approximate data according to the MBE. But knowing the construction cost of each of the roof models used (Table 2) allow to do a comparison not only between renovation cases but also between roof construction systems. According to Table 1, only the waterproof sheet and the upper layers are installed, since it is considered that, when carrying out the renovation, the support structure and the slope formation are in good condition. For the modelled house, of 77.2 m^2, the initial construction cost would be

Table 5
Economic savings (€), due to annual energy savings, comparing the reference model with the A-B-C models in the two renovation scenarios: only roof (Roof) and envelope (Env.).

	A-Env.	A-Roof	B-Env.	B-Roof	C-Env.	C-Roof
Las Palmas de Gran Canaria	−224.28	53.47	−295.41	61.26	−242.97	67.49
Almería	245.57	174.96	180.15	185.86	249.72	209.23
Seville	440.78	245.05	377.44	251.80	431.43	265.30
Barcelona	559.66	265.81	536.30	289.70	558.63	286.58
Madrid	1042.50	362.90	1028.48	393.53	1051.84	389.90
Burgos	1802.04	437.14	1819.69	480.75	1820.21	469.33

2956.76–3808.28 € for the roof with gravel finish (model A), 6615.29–7370.28 € for extensive green roof (model B), and 15,619.88-16,225.12 € for intensive green roof (model C).

It is observed that the construction cost is between 9004.59 and 8854.84 € higher in model C than in model B (more than double than model B cost), while the economic savings obtained with model B are between −69.57 € and 11.42 € compared to model C, depending on the city and renovation case (in no case the difference between savings exceed 30 %).

The construction cost, as well as other factors such as the self-weight of the system, are very decisive when choosing the intervention and construction system to be used, especially in renovation cases. Therefore, it is important to know the energy and economic savings that will be obtained in each of the possible interventions, as well as how long it will take for the initial investment to be made profitable. The NPV (Net Present Value) formula is used, considering that electricity rates will increase by 3 % per year and with a money discount rate of 3 % per year (Fernández-Salvador, 2012). For the specific case of, for example, Seville, the initial investment for the renovation of only the roof with the model B (6714.86 €) would recover after 28 years, while with the model C (15,619.99 €) it would recover after 61 years. These values are justified due to the great difference between the construction costs of both systems, while the difference between the energy and economic savings achieved is not that great. In addition, it should also be considered that model C has disadvantages from the point of view of its self-weight, since the installation of this system supposes a contribution of more than 900 kg/m^2 and in the case of model B, the weight added is less than 170 kg/m^2 (Table 2).

Regarding model A, the initial investment would be recovered in 14 years, but it should be noted that in this economic study a large number of environmental and social benefits that are difficult to quantify are not being evaluated (Table 2). These represent an imbalance in the scales of sustainability in favour of green roofs, since they provide improvements to the environment and society thanks to the renaturalization of cities and the fight against climate change. These variables are hardly visible to the users of the buildings, which is why public administrations have an important role to play in promoting green roofs and all their benefits, for example, with the introduction of discounts or incentives that favour the installation of these more sustainable construction systems.

In the case that a refund of 20 % of the total construction cost of the green roof is applied by the administration, as occurs in Basel (Switzerland) (Shafique et al., 2018), the initial investment of model B would recover at 22 years, a value closer to that of the model A.

The energy savings obtained in these renovation scenarios not only imply an economic benefit due to the lower annual energy expenditure. The electrical energy that is not consumed also means lower CO_2 emissions into the atmosphere, with the consequent benefit for the environment. In addition, the use of extensive and intensive green roofs entails a series of added environmental benefits that are outside the scope of this study but must be assessed when proposing possible renovation solutions. Of the two assumptions studied, in the case of the three roof systems, the final total annual energy savings have been translated into equivalent kilograms of CO_2 (kg CO_2) not emitted into the atmosphere (Table 6). To carry out this conversion, the CO_2 emission equivalence ratios available for Spain have been used, in accordance with the standard (Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2014). For the case studied, whose energy source is electricity, they are: 0.331 kg CO_2/kWh final energy for the peninsula and 0.776 kg CO_2/kWh final energy for the Canary Islands.

Conclusions

On the basis of a single-family semi-detached house (reference model) built before 1980 and, therefore, without any type of insulation in the thermal envelope, the renovation is proposed based on two

Table 6
Reduction in CO_2 emissions (kg CO_2), due to annual energy savings, comparing the reference model with the A-B-C models in the two renovation scenarios: only roof (Roof) and envelope (Env.).

	A-Env.	A-Roof	B-Env.	B-Roof	C-Env.	C-Roof
Las Palmas de Gran Canaria	−931.22	222.02	−1226.53	254.36	−1008.82	280.22
Almería	434.90	309.86	319.05	329.17	442.26	370.54
Seville	780.61	433.98	668.44	445.93	764.07	469.84
Barcelona	991.17	470.76	949.79	513.05	989.33	507.54
Madrid	1846.26	642.70	1821.44	696.95	1862.81	690.51
Burgos	3191.42	774.18	3222.68	851.41	3223.60	831.18

scenarios. It is proposed, on the one hand, only the reduction of the transmittance of the roof and, on the other hand, the reduction of the transmittance of all the elements of the thermal envelope of the building. These two assumptions are developed in 6 different cities of the Spanish territory, according to the division of climatic zones established by standards based on outdoor temperature and solar radiation. In each of the cities, the two renovation scenarios are proposed for three roof construction systems: (i) traditional with a gravel finish (model A), (ii) extensive self-sustaining green roof (model B), (iii) and intensive self-sustaining green roof (model C).

The simulations carried out show that the assumption of renovation of the roof and the one of the entire envelope imply energy savings with respect to the total annual final energy consumption of the reference model, except in the particular case of Las Palmas de Gran Canaria. These energy savings increase at lower outdoor temperatures and greater daily and annual thermal variations.

Regarding the construction system, in the case of renovating only the roof, it is observed that models B and C show greater energy savings than the model A. In cities located in warm climates, the greatest savings are obtained with model C, while in cold climates with model B. This variation responds to design differences, especially to the type of vegetation chosen in each of the models.

The difference between the energy savings obtained with the renovation of the roof and the entire envelope also increases in cold climates.

In warm climates with high solar radiation, an improvement in the thermal transmittance of the roof limits the amount of heat that is transmitted to the interior through this element, leading to greater energy savings. In the case, for example, of Almería, the influence of the energy savings obtained with the renovation of the roof with respect to the savings by improving the entire envelope is 71.26 % in model A, 103.18 % in the model B and 83.85 % in model C.

In cold climates, as the roof only accounts for 47 % of the total square meters of the thermal envelope in contact with the air, its influence in terms of savings is considerably reduced. In Burgos, the influence of the energy savings obtained with the renovation of the roof with respect to the savings by improving the entire envelope is 24.26 % with model A, 26.42 % with model B and 27.75 % with model C.

From all these data, it is concluded that, in cold climates, with less solar radiation and colder temperatures together with greater thermal variations (Burgos or Madrid), the influence of the roof is less. In other words, in these circumstances the energy savings achieved just by renovating the roof are less than half of the savings achieved by renovating the entire envelope. In this type of location, the renovation of only the roof should not be considered a feasible option, especially in multi-storey buildings or in those in which the roof represents a low proportion of the total surface of the envelope in contact with the outside air. On the other hand, in warm climates, with dry summers, high temperatures and direct solar radiation (Almería, Seville or Barcelona), and especially in the case of presenting few daily and annual thermal variations (Las Palmas de Gran Canaria), the influence of the roof is greater, with values close to or greater than 50 %. Therefore, in these climatic zones, the option of improving only the thermal transmittance of the roof can be viable and considered as an appropriate solution.

Concerning the construction system, the three roof models present very similar energy behaviour. The extensive green roof (B) performs better in cold climates with a predominance of heating energy consumption. But is important to consider not only the economic benefits, but also the environmental and social ones, which is why green roof systems are the most suitable from a sustainable point of view. Within these green roof models, the installation of an intensive system (C) implies a higher construction cost and self-weight, therefore, taking into account that the energy savings achieved with the models B and C are very similar (due to the peculiarities of location, orientation and design of green roofs without an irrigation system), model B is presented as the best roof renovation construction system.

The energy savings obtained also allow to know the economic profitability of the different cases studied. The model C, due to its high cost and self-weight, does not appear to be a viable option in the field of renovation, where these two factors can be decisive when choosing which construction techniques and systems to use in energetically refurbishments. On the other hand, despite the fact that the model A has the lowest initial construction cost, it should be noted that green roofs have a wide variety of environmental and social benefits that are difficult to quantify, so it is necessary to carry out a campaign to support and promote the installation of these vegetated roofs, educating users in a global mentality of sustainability.

This study allows knowing in greater detail the variations in energy behaviour according to the most influential variables in each type of climate, as well as depending on the proposed refurbishment. When it comes to energetically renovating a building, it is important to know these variables in order to choose the best constructive and architectural proposal, with which to achieve greater energy savings. Even so, it must be considered, when contemplating the possible renovation and the most appropriate construction systems the non-economic benefits of green roofs, that should not be ignored since they are of great importance in achieving the proposed targets to achieve the goal of becoming more sustainable societies.

Declaration of competing interest

The authors report there are no competing interests to declare.

Acknowledgments

Funding for open access charge: CRUE-Universitat Politècnica de València.

References

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy*, *70*(3), 295–310. https://doi.org/10.1016/S0038-092X(00)00089-X.

Alliance for Sustainable Energy (ASE), L. L. C. (.). OpenStudio. Retrieved fromhttps://openstudio.net/ (Accessed 1 June 2022).

Ascione, F., Bianco, N., De Rossi, F., Turni, G., & Vanoli, G. P. (2013). Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning? *Applied Energy*, *104*, 845–859. https://doi.org/10.1016/j.apenergy.2012.11.068.

Bravo, V. (2016). *Metodología para la simulación energética de un edificio terciario empleando la herramienta Energy Plus*. Universidad Politécnica de Madrid [bachelor thesis].

Carte, T. L., & Rasmussen, T. C. (2006). Hydrologic behavior of vegetated roofs. *Journal of the American Water Resources Association*, *42*(5), 1261–1274. https://doi.org/10.1111/j.1752-1688.2006.tb05299.x.

Ching, F. D. K., & Shapiro, I. M. (2015). *Arquitectura ecológica. Un manual ilustrado*. Editorial Gustavo Gili, SL.

Dietz, M. E. (2007). Low impact development practices: A review of current research and recommendations for future directions. *Water, Air, and Soil Pollution*, *186*, 351–363. https://doi.org/10.1007/s11270-007-9484-z.

EPDM Roofing Association (ERA). (2010). *Life cycle inventory and assessment of selected low slope roofing systems in North America*. TEGNOS Research, Inc.

European Commission (EC). (.). 2030 climate & energy framework. Retrieved fromhttps://ec.europa.eu/clima/eu-action/climate-strategies-targets/2030-climate-energy-framework_en (Accessed 1 June 2022).

Eurostat (2022). Electricity prices for household consumers – bi-annual data (from 2007 onwards). Retrieved fromhttps://ec.europa.eu/eurostat/databrowser/view/NRG_PC_204__custom_2063420/default/bar?lang=en (Accessed 1 June 2022).

Fabbri, K., Tronchin, L., & Barbieri, F. (2021). Coconut fibre insulators: The hygrothermal behaviour in the case of green roofs. *Construction and Building Materials*, *266*, Article 121026. https://doi.org/10.1016/j.conbuildmat.2020.121026.

Fernández-Salvador, V. (2012). Building energy simulation of a zero energy consumption. *DYNA Energía y Sostenibilidad*, *1*(1). https://doi.org/10.6036/ES1012.

Frankenstein, S., & Koenig, G. (2004). *Fast All-Season Soil Strength (FASST).* Cold Regions Research and Engineering Laboratory.

Freney, M., Soebarto, V., & Williamson, T. (2013, August). Thermal comfort of global model earthship in various European climates. *Proceedings of 13th Conference of International Building Performance Simulation Association, Chambéry, France* (pp. 1625–1632).

He, Y., Yu, H., Ozaki, A., & Dong, N. (2020). Thermal and energy performance of green roof and cool roof: A comparison study in Shanghai area. *Journal of Cleaner Production*, *267*, Article 122205. https://doi.org/10.1016/j.jclepro.2020.122205.

Huang, C. C., Busch, C., He, D., & Harvey, H. (2015). *12 green guidelines.* China Development Bank Capital, Ltd.

Instituto para la Diversificación y Ahorro de la Energía (IDAE). (2014). *Factores de emisión de CO2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector de edificios en España.* Ministerio de Industria, Energía y Turismo, Ministerio de Fomento, Gobierno de España.

Instituto para la Diversificación y Ahorro de la Energía (IDAE). (2019). Consumo de energía final. Retrieved fromhttps://sieeweb.idae.es/consumofinal/ (Accessed 1 June 2022).

Instituto Valenciano de la Edificación (IVE). (2011). *Catálogo de Soluciones Constructivas de Rehabilitación.* Generalitat Valenciana.

Instituto Valenciano de la Edificación (IVE). (.). Módulo de edificación y rehabilitación. Retrieved fromhttps://www.five.es/productos/herramientas-on-line/modulo-de-edificacion/ (Accessed 1 June 2022).

International Institute for Applied Systems Analysis (IIASA). (2016). *Water futures and solutions. Fast track initiative.* IIASA.

Jaffal, I., Ouldboukhitine, S. E., & Belarbi, R. (2012). A comprehensive study of the impact of green roofs on buildings energy performance. *Renewable Energy*, *43*, 157–164. https://doi.org/10.1016/j.renene.2011.12.004.

Krzemińska, A., Zaręba, A., & Dzikowska, A. (2017, July). Bioarchitecture - A new vision of energy sustainable cities. *Proceedings of the International Conference on Advances in Energy Systems and Environmental Engineering, Wrocław, Poland*. https://doi.org/10.1051/e3sconf/20172200091.

Lerma, C., Barreira, E., & Almeida, R. M. F. S. (2018). A discussion concerning active infrared thermography in the evaluation of buildings air infiltration. *Energy and Buildings*, *168*, 56–66. https://doi.org/10.1016/j.enbuild.2018.02.050.

Lesjak, V., Pajek, L., & Košir, M. (2020). Indirect green façade as an overheating prevention measure. *Građevinar*, *72*(7), 569–583. https://doi.org/10.14256/JCE.2797.2019.

Liu, T. C., Shyu, G. S., Fang, W. T., Liu, S. Y., & Cheng, B. Y. (2012). Drought tolerance and thermal effect measurements for plants suitable for extensive green roof planting in humid subtropical climates. *Energy and Buildings*, *47*, 180–188. https://doi.org/10.1016/j.enbuild.2011.11.043.

Ministerio de Derechos Sociales y Agenda 2030 (MDSA). (.). Agenda 2030. Retrieved fromhttps://www.mdsocialesa2030.gob.es/agenda2030/index.htm (Accessed 1 June 2022).

Ministerio de Fomento (MF). (2019). *Documento básico HE: Ahorro de energía.* Ministerio de Fomento, Gobierno de España.

Ministerio de Industria, Energía y. Turismo, Ministerio de Fomento (MIET - MF) (2015). *Procedimiento para el reconocimiento conjunto por los Ministerios de Industria, Energía y Turismo y de Fomento de los Documentos reconocidos de certificación energética de edificios.* Ministerio de Industria, Energía y Turismo y Ministerio de Fomento, Gobierno de España [bachelor thesis].

Ministerio de la Presidencia (MP). (2021). *Reglamento de Instalaciones Térmicas en los Edificios (RITE).* Ministerio de la Presidencia, Gobierno de España.

Ministerio de Transportes, Movilidad y Agenda Urbana (MTMAU). (2020). *Actualización 2020 de la Estrategia a largo plazo para la Rehabilitación Energética en el Sector de la Edificación en España (ERESEE 2020).* Retrieved fromMinisterio de Transportes, Movilidad y Agenda Urbana, Gobierno de España.

Mohammadi, K., & Sobouti, H. (2016). Principles of sustainable architecture design in crowded residential complexes with an outlook to resuscitation of nature in architecture. *Turkish Online Journal of Design, Art and Communication*, *6*, 1673–1681. https://doi.org/10.7456/1060AGSE/049.

Nektarios, P. A., Kokkinou, I., & Ntoulas, N. (2021). The effects of substrate depth and irrigation regime, on seeded Sedum species grown on urban extensive green roof systems under semi-arid Mediterranean climatic conditions. *Journal of Environmental Management*, *279*, Article 111607. https://doi.org/10.1016/j.jenvman.2020.111607.

Ouldboukhitine, S. E., Belarbi, R., & Sailor, D. J. (2014). Experimental and numerical investigation of urban street canyons to evaluate the impact of green roof inside and outside buildings. *Applied Energy*, *114*, 273–282. https://doi.org/10.1016/j.apenergy.2013.09.073.

Pandit, R., & Laband, D. N. (2010). Energy savings from tree shade. *Ecological Economics*, *69*, 1324–1329. https://doi.org/10.1016/j.ecolecon.2010.01.009.

Pérez, G., Vila, A., Rincón, L., Solé, C., & Cabeza, L. F. (2012). Use of rubber crumbs as drainage layer in green roofs as potential energy improvement material. *Applied Energy*, *97*, 347–354. https://doi.org/10.1016/j.apenergy.2011.11.051.

Presidencia del Gobierno (PG). (1979). Real Decreto 2429/1979. Retrieved fromhttps://www.boe.es/eli/es/rd/1979/07/06/2429 (Accessed 1 June 2022).

Reyes-Paecke, S., Gironás, J., Melo, O., Vicuña, S., & Herrera, J. (2019). Irrigation of green spaces and residential gardens in a Mediterranean metropolis: Gaps and opportunities for climate change adaptation. *Landscape and Urban Planning*, *182*, 34–43. https://doi.org/10.1016/j.landurbplan.2018.10.006.

Sailor, D. J. (2008). A green roof model for building energy simulation programs. *Energy and Buildings*, *40*, 1466–1478. https://doi.org/10.1016/j.enbuild.2008.02.001.

Santamouris, M., Pavlou, C., Doukas, P., Mihalakakou, G., Synnefa, A., Hatzibiros, A., & Patargias, P. (2007). Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursey school building in Athens,Greece. *Energy*, *32*, 1781–1788. https://doi.org/10.1016/j.energy.2006.11.011.

Schroll, E., Lambrinos, J. G., & Sandrock, D. (2011). An evaluation of plant selections and irrigation requirements for extensive green roofs in the Pacific Northwestern United States. *HortTechnology*, *21*(3), 314–322. https://doi.org/10.21273/HORTTECH.21.3.314.

Serra, V., Bianco, L., Candelari, E., Giordano, R., Montacchini, E., Tedesco, S., Larcher, F., & Schiavi, A. (2017). A novel vertical greenery module system for building envelopes: The results and outcomes of a multidisciplinary research project. *Energy and Buildings*, *146*, 333–352. https://doi.org/10.1016/j.enbuild.2017.04.046.

Shafique, M., Kim, R., & Rafiq, M. (2018). Green roof benefits, opportunities and challenges – A review. *Renewable and Sustainable Energy Reviews*, *90*, 757–773. https://doi.org/10.1016/j.rser.2018.04.006.

Shao, B., Du, X., & Ren, Q. (2018). Numerical investigation of energy saving characteristic in building roof coupled with PCM using lattice Boltzmann method with economic analysis. *Applied Sciences*, *8*, Article 1739. https://doi.org/10.3390/app8101739.

Statista (2021). El sector energético en España. Retrieved fromhttps://es.statista.com/estudio/62746/el-sector-energetico-en-espana/ (Accessed 1 June 2022).

Tiwari, A., Kumar, P., Kalaiarasan, G., & Ottosen, T. B. (2021). The impacts of existing and hypothetical green infrastructure scenarios on urban heat island formation. *Environmental Pollution*, *274*, Article 115898. https://doi.org/10.1016/j.envpol.2020.115898.

U.S. Department of Energy's Building Technologies Office (DOE BTO). (.). EnergyPlus. Retrieved fromhttps://energyplus.net/ (Accessed 1 June 2022).

United Nations (UN). (.). Sustainable Development Goals. Retrieved fromhttps://sdgs.un.org/goals (Accessed 1 June 2022).

Walters, S. A., & Midden, K. S. (2018). Sustainability of urban agriculture: Vegetable production on green roofs. *Agriculture*, *8*(11), Article 168. https://doi.org/10.3390/agriculture8110168.

Wong, N. H., Cheong, D. K. W., Yan, H., Soh, J., Ong, C. L., & Sia, A. (2003). The effects of rooftop garden on energy consumption of a commercial building in Singapore. *Energy and Buildings*, *35*, 353–364. https://doi.org/10.1016/S0378-7788(02)00108-1.

Yang, W., Wang, Z., & Zhao, X. (2015). Experimental investigation of the thermal isolation and evaporative cooling effects of an exposed shallow-water-reserved roof under the sub-tropical climatic condition. *Sustainable Cities and Society*, *14*, 293–304. https://doi.org/10.1016/j.scs.2014.10.003.

Yazdani, H., & Baneshi, M. (2021). Building energy comparison for dynamic cool roofs and green roofs under various climates. *Solar Energy*, *230*, 764–778. https://doi.org/10.1016/j.solener.2021.10.076.

Ziogou, I., Michopoulos, A., Voulgari, V., & Zachariadis, T. (2017). Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm Mediterranean region. *Journal of Cleaner Production*, *168*, 346–356. https://doi.org/10.1016/j.jclepro.2017.08.217.